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OPTIMAL TAXATION ON PROFIT AND POLLUTION WITHIN A MACROECONOMIC FRAMEWORK

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Abstract

In this paper a macroeconomic model of optimal profit taxation developed by Gradus (1991) is extended through incorporation of a tax rate on pollution. It is assumed that the representative firm owns two different stocks of capital goods. The first one is productive but also generates pollution, and the second one is non productive but cleans pollution.

The problem is modelled as a Stackelberg differential game such that the government is the leader; the firms and consumers, each represented by one, are the followers playing Nash against each other. The paper elaborates on the investment and tax policies resulting from the open-loop equilibrium and firm's and consumer's decision problem.

1. INTRODUCTION

In recent years, during which a clean environment becomes more and more a scarce commodity, economists have shown an increasing interest in the problem of reducing the pollution output of firms. An important question in this respect is what kind of policy instruments the government, in its role as social planner, should choose to reduce the level of pollution. In the economic literature it is argued that from an economic point of view the government should try to diminish the firm's pollution by introducing a pollution tax rate rather than imposing laws and/or production restrictions on the firm.

The influence of pollution tax on the behavior of a profit maximizing firm was studied in a paper by Kort, Van Loon and Luptacik (1990). It turned out that the optimal policy of the firm over time mainly depended on the relationships between the values of the different unit costs, in

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which also the pollution tax rate occurs. However, a major drawback of this model is that the policy of the government, i.e. fixing the pollution tax rate, is taken exogenously in the sense that only the behavior of the firm is maximized. By doing this the Lucas critique (cf. Lucas (1976)), which states that the interactions between private and public sector should be evaluated when we want to derive the incidence of different tax rate, is not taken into account. The Lucas critique can be dealt with by modelling the problem as a dynamic game between private and public sector.

Starting point of this paper will be the decentralized market model of Abel and Blanchard (1983) in which the policy of the government was taken exogenously. In this paper a general equilibrium model with utility maximizing consumers and value maximizing firms, which face costs of adjustment, was presented and the incidences of different tax rates were analyzed. We extend this research in two directions. First, we model the government's behavior endogenously, where it maximizes the utility of a representative agent. Here, we assume that the firms and consumers behave atomistically, while the government is the leader within a Stackelberg game. We study the commitment solution of this game. Second, we incorporate a pollution tax rate.

The paper is organized as follows. In Section 2 we model the firms' and consumers' decision problem. Furthermore, the equilibrium in the goods and labor market is described while in Section 3 we present optimal government's behavior under the condition that it takes into account the way that agents make their decisions and that there is an open-loop information structure. Finally, in Section 4 we conclude this paper.

2. THE FIRM'S AND CONSUMER'S DECISION PROBLEM

For reasons of analytical tractability we assume that there is only one representative type of consumer and firm.

2.1. The model of the firm

Consider a firm operating in an environment without exogenous uncertainty. The firm produces a homogeneous output by means of its factors capital and labor. The firm's output can be used for different kinds of public and private spendings. With respect to the production function we assume that capital and labor are substitutes and there is a constant returns to scale technology, so that

$$f = f(k,\ell),\ f(k,0) = 0,\ f(0,\ell) = 0,\ f_k > 0,\ f_\ell > 0,\ f_{\ell\ell}f_{kk} - f_{k\ell}^2 = 0, \quad (1)$$

where f, k and ℓ denote the amount of production, the stock of capital goods and the number of employed workers.

As an inevitable by-product production causes pollution. In the literature there is some discussion about the source of pollution. Van der Ploeg and Withagen (1991) take pollution as a linear function of production, Feichtinger and Luptácik (1987) take a convex function of the labor force. Luptácik and Schubert (1982) have three sources of pollution: consumption, production and the capital stock. Here it is assumed that the amount of pollution is a convex function of capital goods. Furthermore, there is a discussion whether pollution is a stock or flow variable. Some economists take pollution as a stock variable (e.g. Luptácik and Schubert (1982)), while others take pollution as a flow variable (e.g. Feichtinger and Luptácik (1987)). Van der Ploeg and Withagen (1991) investigate the case, where production yields pollution as a stock and a flow. However, it can be shown that the main conclusions of this paper are not affected by this choice. Therefore, we take pollution as a flow variable. Furthermore, it is assumed that this amount of pollution can be reduced through investment in a second kind of capital goods which is nonproductive, but cleans pollution instead. The amount by which pollution output is decreased, is assumed to be a concave function of the stock of those abatement capital goods

$$e = \rho(k) - m(u),\ \rho'(k) > 0,\ \rho''(k) \geq 0,$$

$$\rho(0) = 0,\ m'(u) > 0,\ m''(u) \leq 0,\ m(0) = 0, \quad (2)$$

where e, k and u denote the amount of pollution, the polluted and productive capital stock, and the abatement capital stock, respectively. The firm is confronted with two taxes, because the government asks a proportional tax on profits and pollution. Furthermore, we assume that both investing in capital goods that are productive, as well as in abatement capital goods, generates internal adjustment costs, which in both cases are a convex function of the investment rate

$$\varphi_1 = \varphi_1(i),\ \varphi_1'(i) \gtrless 0 \text{ if } i \gtrless 0,\ \varphi_1''(i) > 0,\ \varphi_1(0) = 0, \tag{3}$$

$$\varphi_2 = \varphi_2(a),\ \varphi_2(a),\ \varphi_2'(a) \gtrless 0 \text{ if } a \gtrless 0,\ \varphi_2''(a) > 0,\ \varphi_2(0) = 0, \tag{4}$$

where φ_1, φ_2, i, a represent the adjustment costs of i, the adjustment costs of a, the investment rate assigned to the productive capital stock and the investment rate assigned to the abatement capital stock, respectively. According to the information described above the present value of the firm's cash flow can be defined as

$$V_0 = \int_0^\infty \{(1-\tau_1)[f(k,\ell) - w\ell] - i - \varphi_1(i) - a - \varphi_2(a) - \tau_2[\rho(k) - m(u)]\}$$

$$\exp[-\int_0^t r(v)dv]dt, \tag{5}$$

in which τ_1, τ_2, w and r denote the proportional tax on profits, the proportional tax on pollution, the wage rate and the interest rate. We assume that the firm takes these taxes and prices as given.

The decision problem of the representative firm is to choose time-paths of investment in both kinds of capital goods and employment that maximize V_0 subject to the accumulation equations:

$$\dot{k} = i - \delta_1 k, \tag{6}$$

$$\dot{u} = a - \delta_2 u, \tag{7}$$

with δ_1 and δ_2 symbolizing the rate of exponential depreciation for both capital goods.

Solving the firm's problem is a straightforward exercise of Pontryagin's maximum principle from which the following necessary conditions for an optimum can be obtained (e.g. Feichtinger and Hartl (1986))

$$- 1 - \varphi_1'(i) + q_1 = 0, \tag{8}$$

$$- 1 - \varphi_2'(a) + q_2 = 0, \tag{9}$$

$$\dot{q}_1 = (r+\delta_1)q_1 - f_k(1-\tau_1) + \tau_2\rho'(k), \tag{10}$$

$$\dot{q}_2 = (r+\delta_2)q_2 - \tau_2 m'(u), \tag{11}$$

$$f_\ell = w, \tag{12}$$

where the symbols q_1 and q_2 stand for the shadow prices of the polluted and abatement capital. From equations (8) and (9) we obtain:

$$i = i(q_1),\ i(1) = 0,\ i'(q_1) > 0, \tag{13}$$

$$a = a(q_2),\ a(1) = 0,\ a'(q_2) > 0. \tag{14}$$

From (6), (8) and (10) we get that the steady-state level of productive capital stock satisfies:

$$(1-\tau_1)f_k = (r+\delta_1)\{1 + \varphi_1'(\delta_1 k^*)\} + \tau_2\rho'(k^*),\ k^*_{\tau_1} < 0,\ k^*_{\tau_2} < 0,\ k^*_r < 0. \tag{15}$$

On the left-hand side of (15) we have the marginal revenue net from profit taxation, while on the right-hand side we find the marginal costs consisting of the sum of the discount rate and depreciation rate, corrected for the fact that $1 + \varphi_1'(\delta_1 k^*)$ dollars are required for a marginal increase of the polluted capital goods level, and of the extra pollution tax that must be paid when the polluted capital stock increases with one unit.

The equations (7), (9) and (11) lead to the following equation for the steady-state level of the abatement capital goods:

$$\tau_2 m'(u^*) = (r+\delta_2)\{1 + \varphi_2'(\delta_2 u^*)\},\ u^*_r < 0,\ u^*_{\tau_2} > 0 \tag{16}$$

Like (15), also (16) is a relation that equates marginal revenue to marginal costs, but now for the abatement capital goods. Notice that the marginal revenue of these capital goods consist of the decrease in pollution tax due to an extra unit of abatement capital goods. From (16) we also infer that if a pollution tax were not introduced, i.e. $\tau_2 = 0$, then the abatement capital stock equals zero. Hence, unlike introducing a profit tax, imposing a pollution tax gives the firm an incentive to invest in abatement capital goods. In this way the tax on pollution will always lead to a reduction of pollution and is thus never preemptive. A straightforward exercise, which can be obtained from the authors upon request, shows that the steady state satisfies saddle point stability (cf. Feichtinger and Hartl (1986, p. 135)).

2.2. The model of the consumer

The welfare of consumers positively depends on private consumption (c), public consumption (g) and negatively on the amount of pollution (e)

$$U_0 = \int_0^\infty u(c,g,e)\exp(-\sigma t)dt, \quad u_c > 0, \; u_g > 0, \; u_e < 0, \tag{17}$$

where σ is a (constant) rate of time-preference. Similar to Abel and Blanchard (1983) and Van de Klundert and Peters (1986) the consumers maximize U_0 with respect to consumption and subject to the dynamic budget constraint

$$\dot{b} = rb + \pi + w\ell - c, \tag{18}$$

where b and π are the amount of bonds held by the consumer and the obtained dividends.

Again the standard solution technique can be applied to obtain necessary conditions for an optimum

$$u_c = x, \tag{19}$$

$$\dot{x} = (\sigma - r)x, \tag{20}$$

where x denotes the costate variable associated to the dynamic budget constraint.

To exclude paths from borrowing forever we assume that there are No-Ponzi-Games

$$\lim_{t\to\infty} \exp\left(-\int_0^t r(v)dv\right)b(t) = 0. \tag{21}$$

In Subsection 2.1 we did not say anything about the way the firms finance their investment. After paying wages to the worker, the firm has to decide how to distribute profit and finance investment by retained earnings or by issuing new shares or bonds. For example, we can assume that replacement investment is financed out of retained earnings and that net investment is financed by bonds. However, because equity and bonds are treated equally by the tax system and there is no uncertainty, the conditions of the Modigliani-Miller theorem hold, thus all financing schemes are equivalent in the sense that they lead to the same path of total consumption and investment; they differ, however, in terms of institutional arrangements (for a proof of this see Abel and Blanchard (1983, pp. 680-681)).

2.3. The markets

In this economy there are two markets: the goods and the labor market. We assume that the goods market is in equilibrium, so that demand is equal to supply

$$f(k,\ell) = c + g + i + \varphi_1(i) + a + \varphi_2(a). \tag{22}$$

From this equation the interest rate r, which is the relative price between current and future consumption, can be derived (e.g. Abel and Blanchard (1983)).

Concerning the labor market we assume that unions behave myopically and that they are shortsighted. According to Oswald (1985) this results in a fixed level of wages. As a consequence of this fixed wage assumption, the capital labor ratio and the marginal productivity of capital are constant, say d and h,

$$\ell = hk, \tag{23}$$

$$f_k = d. \tag{24}$$

In equations (1)-(24) we have an extended version of the decentralized Abel and Blanchard model with pollution. From these equations the optimal values of all variables, except the tax rates τ_1 and τ_2 and government consumption, can be obtained. In the next section we derive the optimal values of these variables.

3. OPTIMAL GOVERNMENT POLICIES

Before we formulate the necessary conditions for an optimal solution we make some additional assumptions. First, we assume that the government has the same utility function as the consumers (cf. Turnovsky and Brock (1980)), and that the consumers' preferences are of Cobb-Douglas type:

$$u(c,g,e) = \alpha \ln c + (1-\alpha)\ln g + \emptyset \ln(\bar{e}-e), \; 0 < \alpha < 1, \; \emptyset > 0. \tag{25}$$

Here $\bar{e}$ can be interpreted as a kind of treshold level (see Dasgupta (1982)), which means that whenever this level is reached the environment is irreparably damaged. Hence, it is very worthwhile for the government to keep the amount of emissions below $\bar{e}$.

Second, there is a balanced budget policy, so that public consumption will be financed from pollution and profit taxation:

$$g = \tau_1\{f(k,\ell) - w\ell\} + \tau_2\{\rho(k) - m(u)\}. \tag{26}$$

Third, as already stated before, the government takes into account the way the consumers and firms behave. In this respect it should be noted that the consumers' co-state variable belonging to the budget constraint, which is denoted by x, can be eliminated. Substitution of (22) into (19) gives us a value for x. This elimination of x stems from the fact that the stream of consumption and investment will not be influenced from financial streams. Similar to the Abel and Blanchard model the consumers only play a passive role through clearing the goods market.

Furthermore, the equilibrium of the goods market gives us the interest rate. Following the approach of e.g. Barro (1979) we treat the interest rate as exogenous to the system.

By using the information obtained until now, the government's problem can be captured in the following optimal control problem:

$$\max_{\tau_1,\tau_2} \int_0^{\infty} (\alpha \,\ell n\, c + (1-\alpha)\,\ell n\, g + \emptyset\,\ell n\,(\bar{e}-e)\exp(-\sigma t)dt \tag{28}$$

s.t.

$$\dot{k} = i(q_1) - \delta_1 k,\ k(0) = k_0 > 0, \tag{29}$$

$$\dot{u} = a(q_2) - \delta_2 u,\ u(0) = u_0 > 0, \tag{30}$$

$$\dot{q}_1 = (r+\delta_1)q_1 - d(1-\tau_1) + \tau_2\rho'(k), \tag{31}$$

$$\dot{q}_2 = (r+\delta_2)q_2 - \tau_2 m'(u), \tag{32}$$

in which:

$$c = (1-\tau_1)dk + whk - i(q_1) - \varphi_1(i(q_1)) - a(q_2) - \varphi_2(a(q_2)) - \tau_2\{\rho(k)-m(u)\}, \tag{33}$$

$$g = \tau_1 dk + \tau_2\{\rho(k)-m(u)\}, \tag{34}$$

$$e = \rho(k) - m(u). \tag{35}$$

The Hamiltonian is defined by:

$$H^G = \alpha\,\ell n[(1-\tau_1)dk + whk - i(q_1) - \varphi_1(i(q_1)) - a(q_2) - \varphi_2(a(q_2)) - $$
$$ - \tau_2\{\rho(k) - m(u)\}] + (1-\alpha)\ell n[\tau_1 dk + \tau_2\{\rho(k) - m(u)\}]$$

$$+ \emptyset\, \ell n[\bar{e} - \rho(k) + m(u)] + \lambda_1\{i(q_1) - \delta_1 k\} + \lambda_2\{a(q_2) - \delta_2 u\} +$$

$$+ \nu_1\{(r+\delta_1)q_1 - d(1-\tau_1) + \tau_2\rho'(k)\} + \nu_2\{(r+\delta_2)q_2 - \tau_2 m'(u)\}, \qquad (36)$$

in which:

λ_1: the government's co-state variable of the stock of productive capital goods

λ_2: the government's co-state variable of the stock of abatement capital goods

ν_1: the government's co-state variable of the firm's co-state variable of the stock of productive captital goods

ν_2: the government's co-state variable of the firm's co-state variable of the stock of abatement capital goods

For an interior solution the necessary conditions are as follows:

$$H^G_{\tau_1} = dk(-\frac{\alpha}{c} + \frac{1-\alpha}{g}) + d\nu_1 = 0, \qquad (37)$$

$$H^G_{\tau_2} = (\rho(k) - m(u))(-\frac{\alpha}{c} + \frac{1-\alpha}{g}) + \nu_1\rho'(k) - \nu_2 m'(u) = 0, \qquad (38)$$

$$\dot{\lambda}_1 = (\sigma+\delta_1)\lambda_1 - \frac{\alpha}{c}\{(1-\tau_1)d + wh - \tau_2\rho'(k)\} - \frac{(1-\alpha)}{g}\{\tau_1 d + \tau_2\rho'(k)\} +$$
$$- \nu_1\tau_2\rho''(k) + \frac{\emptyset}{\bar{e}-e}\rho'(k), \qquad (39)$$

$$\dot{\lambda}_2 = (\sigma+\delta_2)\lambda_2 + m'(u)\{\tau_2(-\frac{\alpha}{c} + \frac{1-\alpha}{g}) - \frac{\emptyset}{\bar{e}-e}\} + \nu_2\tau_2 m''(u), \qquad (40)$$

$$\dot{\nu}_1 = (\sigma-r-\delta_1)\nu_1 + \frac{\alpha}{c}\{i'(q_1)(1 + \varphi_1'(i(q_1))\} - \lambda_1 i'(q_1),\ \nu_1(0) = 0, \qquad (41)$$

$$\dot{\nu}_2 = (\sigma-r-\delta_2)\nu_2 + a'(q_2)\{\frac{\alpha}{c}(1 + \varphi_2'(a(q_2)) - \lambda_2\},\ \nu_2(0) = 0. \qquad (42)$$

Due to the size of the model (four state variables) it is very difficult to prove saddle point stability analytically.

In (37) we find the effects of a marginal profit tax change. A marginal momentarily increase of τ_1 results in an extra income for the government of dk, and this also equals the extra loss for the private sector. Therefore, public consumption increases with dk, which results in an extra utility for the government of $dk(1-\alpha)/g$. Also, the private consumption decreases with dk, due to which utility decreases by $dk\alpha/c$.

Another effect of the increase of profit taxation is that owning productive capital goods becomes less attractive to the firm. This "attractiveness" is measured by the firm's co-state variable of productive capital goods q_1. By solving the differential equation (10) and using the steady state values of q_1 and k as fixed point we obtain the following expression for q_1:

$$q_1(t) = \int_t^{\infty} \{d(1-\tau_1) - \tau_2\rho'(k)\}\exp(-(r+\delta_1)(s-t))ds. \tag{43}$$

From (43) we can conclude that a marginal momentarily increase of τ_1 results in a decrease of q_1 by d units. Due to the fact that ν_1 is the government's co-state variable belonging to q_1, the government values this decrease by $\nu_1 d$. A decrease of q_1 means that the firm values investments to be less attractive, and therefore future productive capital goods and profits decrease, which results in less profit taxation income for the government. Thus, the government will assign a negative value to a decrease of q_1, implying that $\nu_1 d$ is negative so that ν_1 must be negative.

To summarize: an increase of profit taxation implies an increase of public consumption, which is of course a positive effect for the government. But, the negative effects are the decrease of private consumption and the decrease of attractiveness of investing for the firm. The latter results in less future productive capital goods so that future profit taxation income of the government decreases. Now we are able to see that (37) implies that for an interior solution all marginal effects of an increase of τ_1 sum up to zero. This kind of trade off is well known from Ramsey types of models (e.g. Ramsey (1927)).

The implications of a marginal pollution tax change can be found in (38). A marginal increase of the pollution tax rate results in extra taxation income for the government of $\rho(k) - m(u)$. This leads to a shift from private consumption to public consumption and the change in government utility of this consumption effect equals $(\rho(k) - m(u))(-\alpha/c + (1-\alpha)/g)$. Another effect of a higher pollution tax rate is that pollution output becomes more costly to the firm, and therefore the attractiveness of owning polluted capital goods decreases. This attractiveness is measured by q_1 and from (43) we obtain that increasing τ_2 momentarily with one unit leads to a decrease of q_1 with $\rho'(k)$. The government values this decrease with $\nu_1\rho'(k)$.

But, pollution output becoming more costly also implies that owning abatement capital goods, which diminish pollution, becomes more attractive to the firm. This is measured by the firm's co-state variable of abatement capital goods q_2. According to an analogous derivation as for (43), q_2 can be expressed by:

$$q_2(t) = \int_t^\infty \tau_2 m'(u)\exp(-(r+\delta_2)(s-t))dt. \tag{44}$$

Hence, increasing τ_2 by one unit implies an increase of q_2 by $m'(u)$ units, where $m'(u)$ equals the extra decrease of pollution output due to a marginal increase of u. The government values this increase of q_2 by $-\nu_2 m'(u)$, because ν_2 is the government's co-state variable of q_2. The fact that the abatement capital goods become more attractive to the firm is positively valued by the government, because it implies that the firm's pollution output will decrease. Hence, ν_2 will be negative.

To summarize: an increase of the pollution tax rate has a consumption and a pollution effect. Due to a higher tax income there will be a shift from private to public consumption. The fact that polluting the environment becomes more expensive for the firm implies that the attractiveness of the polluted capital goods decreases and the attractiveness of the abatement capital goods increases. Equation (38) says that within the interior solution the consumption effect and the pollution effect of a marginal increase of the pollution tax rate sum up to zero. As already stated in Section 2, imposing a pollution tax rate gives the firm an incentive to invest in abatement capital goods.

From the negativity of ν_1 and (37) we can conclude that marginal utility from public consumption $((1-\alpha)/g)$ is less than marginal utility from private consumption. The government gives up a piece of its government consumption to stimulate capital accumulation. This is contrary to Fischer (1980) where marginal utility from private consumption equals marginal utility from public consumption.

4. CONCLUSIONS

In this paper the impact of profit and pollution tax on dynamic firm behavior is studied within a general equilibrium model. The tax rates are determined endogenously by assuming that the government maximizes utility. The problem is formulated as a Stackelberg differential game with the government as leader, which is studied for the open-loop. The optimal level of the firm's capital stock is determined by an equality between net marginal revenue and marginal costs, where the latter consist of the cost of capital, corrected for adjustment costs, plus marginal pollution tax expenses. In the open-loop Stackelberg equilibrium the optimal pollution tax rate is such that marginal consumption and pollution effects sum up to zero. The pollution effect arises from the fact that in the open-loop case it is possible for the government to deviate from short term optimality. This effect states that announcing a policy of high pollution tax implies that investing becomes less attractive to the firms, because more production generates more pollution as an inevitable byproduct and the latter is punished more heavily. On the other hand the firms are stimulated more to spend more money in ways to diminish their own pollution. The summation of these two effects gives us the pollution effect.

In future research there are many avenues to explore. First, it would be interesting to extend the framework to other sources of pollution like consumption and production. In that case the efficiency consideration of taxation depends on the source of pollution. Second, in this paper we have only derived the open-loop Stackelberg equilibrium. However, it can be shown that this equilibrium is time-inconsistent and it is only credible if there are reputational forces or binding contracts. Therefore, it would be interesting to calculate the feedback Stackelberg equilibrium and to calculate the welfare gain if the government commits itself to its announced policy. Third, it is also possible to incorporate environmental standards in the model and to describe the trade off between the tax instruments and standards in order to reduce pollution. Finally, the introduction of political issues could be an important extension.

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